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14. ABSTRACT

Our aim was to develop quantitative models to predict and prevent errors in spatial orientation and sensory localization during exposure to the novel forces of aerial environments. Most of our effort focused on localization of the subjective vertical. The accomplishments of the project were: 1) we acquired the requisite data to build a three-dimensional model of static vestibular orientation, 2) we built a novel static vestibular orientation model based on biological principles, and 3) we acquired additional data to independently test our model against other models. Our model fit our new data as well as all existing data which had been collected in 1 g and in various hyper-g centrifuge experiments. The model made different predictions than every other model about orientation in the yaw axis in hyper-g environments, and this prediction turned out to be correct. Thus, our final model makes the most comprehensive, accurate predictions of orientation errors in multi-force backgrounds. It also implies that somatosensory cues will have a heightened role in negative-g situations. We also collected data to help extend our model to dynamic situations.

15. SUBJECT TERMS

Spatial Orientation, Disorientation, Localization, Multi-sensory, Vestibular, Somatosensory, Model

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Multisensory spatial orientation and localization
In novel gravitoinertial force backgrounds

AFOSR grant F49620-01-1-0171

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Objective

The stated goals of this project were 1) to develop a quantitative model of the effects of gravitoinertial force and of visual fields on apparent body orientation and multisensory localization and 2) to use this model to predict which flight conditions will produce spatial disorientation and whether sensory cueing systems can be developed to enhance accurate spatial orientation and sensory localization.

Status of effort

Our original goal was to investigate a single dimension of body orientation – orientation in the yaw plane. However, as we began to model how humans localize the subjective vertical, it became apparent that a vestibular model of yaw orientation could not be constructed independently of the other axes, because the structure of the vestibular otolith organs intrinsically cross-couples the afferent information about different axes of stimulation. The multi-dimensional models in the literature had all been constructed on the basis of only pitch and roll axis data. By the end of the project we 1) acquired the necessary yaw data to build a three-dimensional model, 2) built the model, and 3) acquired data to independently test our model against other models. Our initial model fit our new yaw data collected in a normal 1 g environment as well as all the existing pitch and roll data which had been collected in 1 g and in various hyper-g centrifuge experiments. The model made different predictions than every other model about orientation in the yaw axis in hyper-g environments, and this prediction turned out to be correct. Thus, our final model makes the most comprehensive, accurate predictions of orientation errors in multi-force backgrounds. It also implies that somatosensory cues will have a heightened role in negative-g

situations. In the course of our investigations, we also collected data which will help extend our model to predict orientation in dynamic situations.

Accomplishments/New Findings

Spatial disorientation in flight leads to the death of many aircrew members and costs millions of dollars each year. The aerial environment can produce disorientation because it has many novel features to which our sensorimotor systems are not attuned. Much past work on spatial disorientation has focused on the visual and vestibular systems and their interaction in influencing apparent orientation. Such work has demonstrated a variety of illusions associated with exposure to unusual gravitoinertial force fields. In these illusions, visual and auditory stimuli that are spatially fixed in relation to the observer appear to change their body relative positions – the oculogyral and audiogyral illusions, respectively. Such illusory localization has never been measured simultaneously with apparent orientation in situations analogous to aerial environments which produce significant vestibular stimulation. Our goal was to develop quantitative models for predicting and preventing disorientation and mislocalization.

Our accomplishments during this project included:

1. We acquired the requisite psychophysical data for building a three-dimensional vestibular model of static spatial orientation. (Bortolami, Pierobon, DiZio & Lackner, 2006)
2. We built a novel static vestibular orientation model which fit a comprehensive three-dimensional data set. (Bortolami, Rocca, DiZio, Lackner, 2006)
3. We acquired new data in parabolic flight and in our rotating room to independently test our model against other models. (Bryan, Bortolami, Ventura, DiZio & Lackner, submitted)
4. We obtained data to extend our static model to dynamic conditions by evaluating perceived angular displacement during tilt of the body relative to the gravitoinertial vertical in parabolic flight. (Lackner, Ventura & DiZio, 2006)
5. We assessed multi-sensory localization during angular acceleration, which complements our ongoing studies of orientation and localization during linear acceleration. (A. Bryan thesis)
6. We assessed visual-vestibular interactions during vertical linear oscillation, to move toward a model which incorporates visual and vestibular interactions. (Wright, DiZio & Lackner, 2005, 2006)

Each of these items is explained in more detail below:

1. <u>Acquire requisite psychophysical data for building a three-dimensional vestibular model of static spatial orientation</u>. Localization of the subjective vertical during body tilt in pitch and in roll has been extensively studied because of the relevance of these axes for aviation and control of posture. Studies of yaw orientation relative to gravity were lacking. We performed the first thorough evaluation of static orientation in recumbent yaw and collected as efficiently as

possible roll and pitch orientation data which would be consistent with the literature, using the same technique as our yaw tests. This created the first comprehensive, coherent data set for all three axes suitable for quantitative tri-dimensional modeling of spatial orientation. We tested localization of the vertical for subjects tilted in pitch (-100º to +130º), in roll (-90º to +90º), and in yaw while recumbent (-80º to +80º). We had subjects point a gravity-neutral probe to the gravitational vertical (haptically indicated vertical) and report verbally their perceived tilt. Subjects underestimated their body tilts in recumbent yaw and pitch and overestimated their tilts in roll. The haptic settings for pitch and roll were consistent with data in the literature obtained with haptic and visual indications. Our data constitute the first tri-dimensional assessment of the subjective vertical using a common measurement procedure and provide the basis for tri-axial modeling of vestibular function.

2. <u>Novel static vestibular orientation model</u>. We developed a tri-axial model of spatial orientation applicable to static 1 *g* and non-1 *g* environments. The model captures the mechanics of otolith organ transduction of static linear forces and the perceptual computations performed on these sensor signals to yield subjective orientation of the vertical direction relative to the head. The perceptual component of our model embodies the idea that the central nervous system processes utricular and saccular stimuli as if they were produced by a gravitoinertial force (GIF) vector equal to 1 *g*, even when it differs in magnitude because in the course of evolution living creatures have always experienced gravity as a constant. The perceptual model also embodies the idea that the CNS determines just two independent angles of head orientation relative to the vertical which are GIF-dependent, the third angle being derived from the first two and being GIF-independent. By contrast, other models compute the GIF vector in three independent dimensions. Somatosensory stimulation is used to resolve our vestibular perceptual model's ambiguity of the up-down directions. Our otolith mechanical model takes into account recently established non-linear behavior of the force-displacement relationship of the otoconia, and possible otoconial deflections that are not co-linear with the direction of the input force (cross-talk). The free parameters of our model relate entirely to the mechanical otolith model. They were determined by fitting the integrated mechanical/perceptual model to subjective indications of the vertical obtained during pitch and roll body tilts in 1 *g* and 2 *g* force backgrounds and during recumbent yaw tilts in 1 *g*. The complete data set was fit with very little residual error. A novel prediction of the model is that background force magnitude, either lower or higher than 1 *g,* will not affect subjective vertical judgments during recumbent yaw tilt.

3. <u>Independent test of static vestibular orientation model</u>. We set out to test the prediction of our three-dimensional model of static vestibular orientation that subjective vertical settings in the recumbent yaw axis will not change as a function force gravitoinertial force magnitude. Our approach was to measure the subjective vertical and apparent head midline of recumbent subjects (n=6) while they were tilted at various angles about their yaw axis. One set of tests was

conducted during parabolic flight maneuvers where the background gravitoinertial acceleration varied from 0 to 1.8 g. The blindfolded subjects were tested supine and at tilts of 60° and 30° left and right about their horizontal long body axis. They used a gravity neutral joystick to indicate their subjective vertical or their head midline continuously from the high force through the 0 g portions of parabolas. Settings of the subjective vertical did not differ between 1 g and 1.8 g test conditions. Subjective vertical measure measurements were also made in the Brandeis slow rotation room (n=11), with the room stationary and rotating at a speed which produced a 2 g resultant of gravitational and centrifugal acceleration. There were no differences in settings of the subjective vertical between 1 g and 2 g, in parabolic flight and in the rotating room, which is consistent with our model. The contrasting and well known g dependencies of subjective vertical settings in the pitch and roll axes are also consistent with our model. A surprising finding was that in 0 g in parabolic flight, all subjects felt horizontal and they oriented the joystick perpendicular to their body when indicating the subjective vertical. This points to a strong influence of somatic touch and pressure cues when the otolith organs are unloaded.

4. <u>Perceived angular displacement during body tilt in different force backgrounds</u>. The experiment presented in the previous section showed that subjects always localized the subjective vertical in their body mid-sagittal plane when they were rotated and then held in different static recumbent yaw orientations, in 0 g, “weightless”, conditions. The alignment of the subjective vertical with the body midline in 0 g may be due to the evenly distributed contact cues. However, we were surprised that integration of semi-circular canal signals present when we tilted the subjects did not influence the post-turn orientation judgments. To evaluate how angular velocity information from the canals is integrated in different force backgrounds, we evaluated the ability of subjects being rotated about their recumbent yaw axis to continuously point to the subjective vertical, in 1g, 1.8g and 0g. Seven subjects (24 to 60 years of age) were tested, blindfolded and wearing ear plugs. They were strapped into a tiltable, padded bed mounted parallel to the fuselage of NASA’s KC-135 aircraft. The bed could be tilted +/-60° from the horizontal plane. The aircraft flew parabolic trajectories, producing alternating periods of 1.8 g and 0 g, each lasting approximately 25 seconds. 1 g testing was carried out both in straight and level flight and on the ground. Each trial consisted of a quick, manual 30°, 60° or 120°amplitude displacement of the bed, which had been pre-positioned in a semi-random starting position. The subject’s task was to align a gravity-neutral pointer with their subjective vertical while in the static initial position and to keep it aligned throughout the subsequent displacement. In 1 g and 1.8 g, subjects aligned the joystick quite accurately with the true vertical before the tilt and counterrotated it during the angular displacement to keep it aligned with the vertical. During static tilts in 0 g subjects felt horizontal and aligned the pointer with their body midline, which we attribute to evenly distributed somatosensory cues. Subjects did not counterrotate the stick during the 0g bed rotations, which were above threshold for detection by the semicircular canals. The absence of

indicated self-rotation relative to the subjective vertical in 0g could be due to a breakdown of angular path integration, an unchanging somatosensory "vertical" superceding the canal cues, or a combination of the two.

5. Multi-sensory localization during angular acceleration. One goal of this set of experiments was to quantitatively record the relationship between vestibularly driven eye movements (nystagmus) and localization of a visual target relative to the head (the oculogyral illusion, OGI). This involved tracking a target light with a pointing device, as well as following it with the eyes. Another goal was to compare the OGI with our perception of the head midline position. This required the subjects to stare straight ahead, and point along their head midline during rotary acceleration in the dark. The measure of the nystagmus in the dark conditions could then be compared with that of the light tracking trials. The difference between the amount of nystagmus in the dark and target tracking trials would give a measure of the amount of oculomotor suppression required to keep the target foveated. The first finding was that the magnitude and timing of suppression was highly correlated with the oculogyral illusion itself. A second finding was that the perceived position of the head midline was displaced in the direction opposite of acceleration, in the dark trials. This magnitude of displacement was similar to that of the oculogyral illusion, and its peak displacement occurred at the same time as that of the OGI. Finally it was found that the head midline illusion occurred with or without the presence of a light target. These results imply that the head midline illusion may be partially responsible for the oculogyral illusion. In general, dynamic vestibular stimulation alters sensory localization through both modality specific pathways and multi-modal representations of body orientation.

6. Visual-vestibular interactions during vertical linear oscillation. We evaluated visual and vestibular contributions to vertical self motion perception by exposing subjects to various combinations of 0.2 Hz vertical linear oscillation and visual scene motion. The visual stimuli were presented via a head-mounted display and consisted of video recordings of the test chamber from the perspective of the subject seated in the oscillator. In the dark, subjects accurately reported the amplitude of vertical linear oscillation with only a slight tendency to underestimate it. In the absence of inertial motion, even low amplitude oscillatory visual motion induced the perception of vertical self-oscillation. When visual and vestibular stimulation were combined, self-motion perception persisted in the presence of large visual-vestibular discordances. A dynamic visual input with magnitude discrepancies tended to dominate the resulting apparent self-motion, but vestibular effects were also evident. With visual and vestibular stimulation either spatially or temporally out-of-phase with one another, the input which dominated depended on their amplitudes. High amplitude visual scene motion was almost completely dominant for the levels tested. These findings are inconsistent with self-motion perception being determined by simple weighted summation of visual and vestibular inputs and constitute evidence against sensory conflict models. They indicate that when the

presented visual scene is an accurate representation of the physical test environment, it dominates over vestibular inputs in determining apparent spatial position relative to external space.

In a second experiment, we evaluated the influence of moving visual scenes and knowledge of spatial and physical context on visually induced perception or vertical linear oscillation. A sinusoidal, vertically oscillating visual stimulus presented in an immersive virtual environment induced perceptions of self-motion that matched changes in visual acceleration. Subjects reported peaks of perceived self-motion in synchrony with peaks of visual acceleration and opposite in direction to visual scene motion. Spatial context was manipulated by testing subjects in the physical environment that matched what was depicted in the virtual scene or by testing them in a separate chamber. Physical context was manipulated by testing the subject while seated in a stable, earth-fixed desk chair or in an apparatus capable of large linear motions, however, in both conditions no actual motion occurred. The compellingness of perceived self-motion was increased significantly when the spatial context matched the visual input and actual body displacement was possible, however, the latency and amplitude of perceived self-motion were unaffected by the spatial or physical context. We propose that two dissociable processes are involved in self-motion perception: one process, primarily driven by visual input, affects vection latency and path integration, the other process, receiving cognitive input, drives the compellingness of perceived self-motion.

Publications and Presentations

DiZio P, Lackner JR, Held RM, Shinn-Cunningham B, Durlach NI. Gravitoinertial force magnitude and direction influence head-centric auditory localization. J. Neurophysiol., 85: 2455-2460, 2001.

Lackner JR, DiZio P. Multisensory influences on orientation and movement control. In: The Handbook of Multisensory Processes, Calvert G, Spence C, Stein B (eds), MIT Press, pp. 409-423, 2004.

Wright WG, DiZio P, Lackner JR. Vertical linear self-motion perception during visual and actual-inertial stimulation: more than weighted summation of sensory inputs. J. Vestib. Res., 15: 185-195, 2005

Lackner JR, DiZio P. Vestibular, proprioceptive, and haptic contributions to spatial orientation. Annual Review of Psychology, 56: 115-147, 2005.

Wright WG, DiZio P, Lackner JR. Perceived self-motion in two visual contexts: dissociable mechanisms underlie perception. J Vestib Res.;16:23-8, 2006

Bortolami SB, Pierobon A, DiZio P, Lackner JR. Localization of the subjective vertical during roll, pitch, and yaw body tilt. Exp Brain Res, 173:364-73, 2006

Bortolami SB, Rocca S, DiZio P, Lackner JR. Mechanisms of human static spatial orientation. Exp Brain Res, 173:374-88, 2006

Lackner JR, DiZio P. Space motion sickness. Exp Brain Res, 2006 Oct 5; [Epub ahead of print]

Lackner JR, Ventura J, DiZio P. Dynamic spatial orientation in altered gravitoinertial force environments Society for Neuroscience Abstracts, Abstract No 244.11, Atalnata, GA, Oct 14-18, 2006)

Bryan A, Bortolami SB, Ventura J, DiZio P, Lackner JR. Influence of Gravitoinertial Force Level on the Subjective Vertical During Recumbent, Yaw Axis, Body Tilt. In submission.

Interactions

Dr. Lackner was an invited panelist at two government sponsored meetings concerned with spatial orientation problems, and he gave the following presentations:

1. Lackner, JR, DiZio P. Gravitoinertial force magnitude and direction influences visual, auditory, and somatosensory localization. Symposium on Situational Awareness in Spatial Orientation Tasks, AFOSR, San Antonio TX, October 2000.
2. Lackner, J.R. Spatial orientation and motor control in altered force backgrounds. DARPA Spatial Disorientation Knowledge Acquisition Workshop, Rosslyn, VA, December 2001

Dr Dizio was an invated panelist at several NASA sponsored meetings focused on space medicine problems including spatial orientation, locomotor instability and motion sickness in astronauts.

1. DiZio P, Lackner JR. Somatosensory suppression and prevention of post-flight re-entry disturbances of posture and locomotion. NSBRI Annual Meeting, Clear Lake, TX, February 26-March 1, 2006

2. DiZio P, Lackner JR. Sensory-motor Adaptation to Artificial Gravity. NASA Bioastronautics meeting, Galveston, TX, January 9-12, 2005.

Patent Report

No inventions were produced.